REVIVING URBAN STREAMS: LAND USE, HYDROLOGY, BIOLOGY, AND HUMAN BEHAVIOR[1]

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ABSTRACT: Successful stream rehabilitation requires a shift from narrow analysis and management to integrated understanding of the links between human actions and changing river health. At study sites in the Puget Sound lowlands of western Washington State, landscape, hydrological, and biological conditions were evaluated for streams flowing through watersheds with varying levels of urban development. At all spatial scales, stream biological condition measured by the benthic index of biological integrity (B-IBI) declined as impervious area increased. Impervious area alone, however, is a flawed surrogate of river health. Hydrologic metrics that reflect chronic altered streamflows, for example, provide a direct mechanistic link between the changes associated with urban development and declines in stream biological condition. These measures provide a more sensitive understanding of stream-basin response to urban development than does treatment of each increment of impervious area equally. Land use in residential backyards adjacent to streams also heavily influences stream condition. Successful stream rehabilitation thus requires coordinated diagnosis of the causes of degradation and integrative management to treat the range of ecological stressors within each urban area, and it depends on remedies appropriate at scales from backyards to regional stormwater systems.

Key terms: aquatic ecosystems, flow, IBI, homeowner behavior, residential conditions, stream rehabilitation, urban water management.

INTRODUCTION

The movement of people from farms to cities began thousands of years ago, accelerated in the twentieth century, and continues into the twenty-first century. By one estimate, 83% of people in Europe and the Americas will live in cities by 2025 (Sheehan, 2001). Urbanization

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alters river ecology in and downstream of cities, harming aquatic systems and prompting efforts to protect, rehabilitate, and even fully restore urban streams. Yet these efforts seldom succeed, mostly because of narrowly prescriptive solutions that do not take advantage of interdisciplinary knowledge in the physical, biological, and social sciences or because they do not treat the full range of urban change in streams (Karr and Rossano, 2001).

In the Pacific Northwest, where continued decline and now Endangered Species Act listings of the region's salmonids fuel public and government agency interest in watershed management, such interdisciplinary efforts are long overdue. Major expenditures are expected over the next decade in the name of "stream enhancement" and purported salmon restoration. Historically, similar expenditures have gone toward narrow fixes of single perceived problems, such as urban runoff, or toward treating symptoms, such as absence of woody debris in streams, rather than root causes, such as alterations in hydrology, riparian vegetation, and human attitudes and behavior. Too often, imperfect analyses combine with conflicting socioeconomic interests and politics to limit rehabilitation success. Yet the region needs integrative and diagnostic approaches to maintain its quality of life for people and stream biota. This report describes work that integrates channel hydrology, river biology, and human activity at diverse spatial scales to improve the condition of urban streams.

This study sets up a conceptual framework for assessing stream degradation and uses it to recommend realistic improvements. Few urban streams can be entirely restored—that is, returned to a state that supports the full range of living things and ecological processes characteristic of the least-disturbed streams of similar size and slope in a region. Many urban streams can, however, be *rehabilitated*—that is, their biological condition (state or health) can be improved to some degree. The framework used here explicitly links the human actions collectively termed "urbanization" with biological condition, the primary endpoint of concern (Figure 1). Urbanization does not itself cause biological decline; instead, it alters the landscape, inflicting stresses on stream biota. Successful stream rehabilitation requires understanding the many stressors and their interactions, which link human actions to biotic changes (e.g., Grimm et al., 2000). This complexity demonstrates the futility of one-size-fits-all urban restoration.

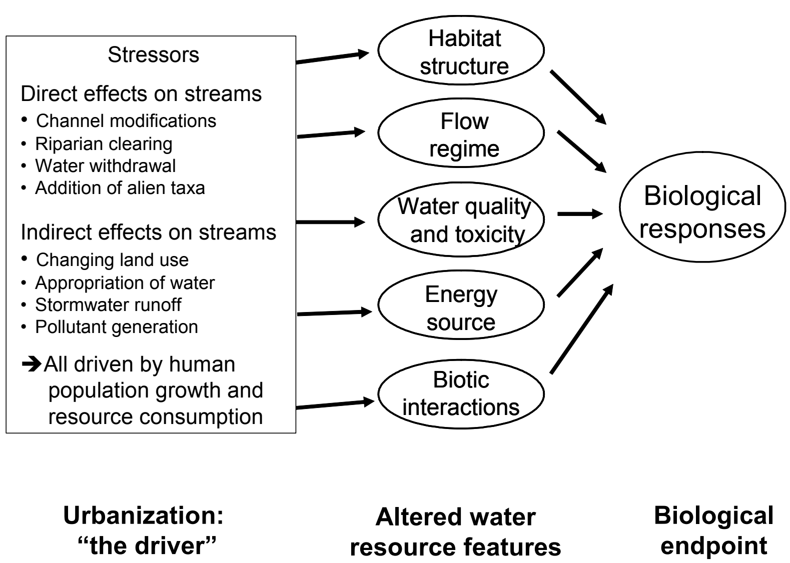

Figure 1. Conceptual model of the varied stressors resulting from human actions that alter stream biological condition. (Modified from Karr and Yoder, 2004).

This study focuses on the effects of human actions at spatial scales ranging from backyards to urbanization of entire subbasins. The study emphasizes the effects of such actions on channel hydrology and, in turn, outcomes in the biological condition of urban streams. Development-induced flow alteration was neglected in recent decades, when water chemistry dominated water resource management. Recent studies in the Northwest, however, suggest little if any relationship between water quality parameters and biological health in lightly to moderately urbanized watersheds (May et al., 1997; Horner and May, 1999). Thus, the focus here is on other factors likely to display significant relationships.

URBANIZATION IS NOT A SIMPLE PHENOMENON

Stream degradation caused by urbanization is not a single problem with a single solution, or even a well-defined set of problems with well-defined solutions. Rather, stream degradation results from a collection of individual decisions and actions that leads to specific urban landscapes and, in turn, to altered stream condition. "Urbanization" itself is multidimensional and has been defined in many different ways (McIntyre et al., 2000). It may constitute industrial, retail, or housing development; it may proceed quickly or gradually. It can be halted at an early stage by zoning or hastened by incentives that encourage development. An urbanized watershed may contain polluting or nonpolluting industries, dense road networks or only a few roads. The topography, soils, vegetation, and channel networks in an urban basin may be altered. Thus no single change defines urbanization; instead, the cumulative effect of the variety of human activities in urban basins profoundly influences urban streams and their biota (Figure 2). Because of this complexity, successful rehabilitation must combine knowledge of the biophysical processes and conditions that sustain a specific stream system with knowledge of the drivers of degradation in that system.

Figure 2. Juanita Creek in the Puget Sound lowlands, heavily influenced by intensive human land use throughout its watershed.

STUDY REGION AND SITES

Streams within the Puget Sound lowlands of western Washington State share relatively uniform physical and biological environments, which allow direct comparisons among streams. For this study, 45 sites from 16 second- and third-order streams in King, Snohomish, and Kitsap Counties (Figure 3) were selected with the following characteristics: watershed area between 5 and 69 km^2; local channel gradients between 0.4 and 3.2 percent; climate, elevation, and soils typical of the central Puget Sound lowlands; historical presence of anadromous salmonids; and urban development as the dominant human activity. Selected sites matched these factors but varied in level of urbanization from low-disturbance, or “reference,” locales to intensively urbanized watersheds. Some watersheds still support regionally valuable biological resources, such as anadromous and resident salmonids or diverse invertebrate assemblages; others do not.

Figure 3. Puget Sound region with location of the study streams and watersheds. Area of major urban centers are stippled; study watersheds are shaded.

STUDY DESIGN AND METHODS

The nature, and the causes, of change to aquatic system health were explored along a gradient of human activity (the primary independent variable), characterizing intensity of “human activity” with two common measures of land cover: urban land cover and total impervious area. Both characterizations used a 1998 Landsat image classified into seven land-cover categories at 30 m resolution, which included three “urban” classes (intense, grassy, and forested); three predominantly vegetated classes (grass/shrub, deciduous, and coniferous); and open water (Hill et al., 2003). Percentages for the three urban classes were summed to equal “urban land cover.”

Total impervious area (TIA) is the fraction of a watershed covered by built surfaces or bare ground, such as unpaved roads or trails, that are presumed not to soak up water. On the basis of airphoto interpretation of representative areas across the study area, individual TIA factors were determined for each of the seven land-cover classes (Hill et al., 2003). For six sites that lacked direct measurement, TIA was estimated from the correlation between road density and TIA from eight other study watersheds ($r = + 0.96$, $p < 0.001$). Hydrologically this TIA definition is incomplete, because it ignores supposedly "pervious" surfaces that are compacted or otherwise so nearly impermeable that runoff rates from them are similar to or the same as those from pavement. In addition, it includes some paved surfaces that are small or isolated. Runoff from such areas may be absorbed by adjacent pervious surfaces and thus contribute nothing to the storm runoff response of the downstream channel. Nevertheless, this study follows the common practice of using TIA as a primary index of urbanization, recognizing that it is an imperfect measure of not only human disturbance but also the diverse hydrologic, chemical, physical, and biological stressors and their consequences that follow urban development.

The primary dependent variable is stream health, measured using the 10-metric benthic index of biological integrity (B-IBI; Karr, 1998). B-IBI includes measures of taxa richness, tolerance of disturbance, dominance, and characteristics of selected ecological groups (e.g., clingers, predators). From 1995 to 1999, benthic invertebrates were collected during September, when flows are typically stable, taxa richness is high, and sites are easy to get to (Morley and Karr, 2002; 1995 data from J. R. Karr, unpublished). At each site, a Surber sampler (500 µm mesh) was used to collect three replicate 0.1 m^2 samples along the midline of a single riffle. Samples were preserved in the field and identified in the lab, generally to genus, without subsampling (as recommended by Karr and Chu, 1999). Sites with biological conditions at or near the condition of minimally influenced "reference" streams were given a score of 5, while moderately or severely degraded streams were scored 3 and 1, respectively. Scores for each of the 10 metrics are summed to yield site B-IBIs ranging from 10 to 50, divided into descriptive classes of excellent (46–50), good (38–44), fair (28–36), poor (18–26), and very poor (10–16). The B-IBI for each site provides a robust and convenient way to explore the relationships between land cover and overall biological condition.

The relationship between human influence (urban land cover) and biological condition (B-IBI) were examined at three spatial scales for each sample site: ***subbasin*** (i.e., the entire watershed upstream of the sample site); ***riparian*** (a 200-m-wide buffer on each side of the stream extending the full length of the upstream drainage network); and ***local*** (a 200-m-wide buffer on each side of the stream extending 1 km upstream (Morley and Karr, 2002).

Hydrologic consequences of urban development have long been documented for individual storms (Leopold, 1968; Hollis, 1975), but such consequences over longer periods are scarcely explored. Because longer term effects should be especially important to stream biota (e.g., Shelford and Eddy, 1929; Odum, 1956; Horwitz, 1978; Poff and Allan, 1995; Poff et al., 1997), two hydrologic metrics were developed to represent stormflow and baseflow patterns over multiple-year periods (Konrad and Booth, 2002): the fraction of a year that the daily mean discharge exceeds the annual mean discharge (T_{Qmean}); and the fraction of a multiple-year period that streamflow exceeds the discharge of the flood peak that occurs, on average, twice each year ($T_{0.5\ yr}$). Streamflow patterns were analyzed for water years 1988 to 2000 (water years begin on October 1) using records from 15 gaging stations within 5 km of B-IBI sampling sites and without large intervening tributaries (Table 1).

T_{Qmean} measures daily streamflow through time relative to the mean discharge of a stream. The annual mean discharge (Q_{mean}), which is not strongly altered by urban development (Konrad and Booth, 2002), serves as a basis for normalizing streamflow patterns in comparisons among streams. The number of days when daily mean discharge (Q_{daily}) exceeded Q_{mean} were calculated for each year of record for each stream. T_{Qmean} was then calculated as the average annual fraction of a year that Q_{daily} exceeded Q_{mean} (commonly about 100 days per year for the streams in this study), which yields lower fractions for “flashy” streams and higher fractions for gradually varying flow regimes.

Table 1. Puget Sound lowland stream study sites.

Stream	Site ID	Subbasin % TIA	Local % urban	T_{Qmean}	$T_{0.5\ yr}$	B-IBI
Big Beef	BB_1995	5		0.28	0.009	26
Rock	RO971/982	9	14	0.39	0.034	48
Big Bear	BB974	15	37	0.33	0.011	34
Covington	CV_1995	16		0.37	0.054	42
May	MA971	19	34	0.32	0.014	24
Jenkins	JE971	21	56	0.42	0.020	32
Big Soos	BS971	33	55	0.34	0.039	26
North	NO982	35	44	0.30	0.005	22
Hylebos	HY_1995	37		0.32		22
Swamp	SW982	38	53	0.31	0.003	28
Des Moines	DM_1995	39		0.27	0.002	16
Mercer	KE_1995	46		0.26	0.003	12
Thornton	TH98DS	51	89	0.29	0.004	12
Miller	MI971	54	45	0.26	0.002	12
Juanita	JU_1995	59		0.28		10

$T_{0.5\ yr}$ is an equivalent measure of streamflow through time, but instead of using a common discharge (Q_{mean} equaled or exceeded 1/3 of the time), this metric records the fraction of time that a stream channel is exposed to flows whose magnitude exceeds a more significant, less common flow. This metric also reflects the influence of urbanization on hydrology because high flows tend to increase in frequency, but not in duration, in response to urban development; that is, individual high-flow events occur more often with more development. A significant relationship between this hydrologic parameter and stream health was anticipated because field data show that frequent high flows continually destabilize channels rather than develop a new equilibrium form (Konrad et al., 2002). The 0.5-year flood, calculated from a partial-duration series of peak discharge (Langbein, 1949), was chosen as the discharge index because it has plausible geomorphic and biological significance: half-year floods occur often enough to exert persistent effects on stream biota (typically occurring about 100 *hours* per year in the sample set), and they transport streambed sediment in most alluvial channels (Pickup and Warner, 1976; Sidle, 1988). Values of $T_{0.5\ yr}$ were log-transformed before testing for correlations with impervious area and B-IBI.

In addition to hydrologic impacts, any integrative regional effort to rehabilitate urban streams must incorporate understanding of the behavior of individual landowners, because small lowland streams in western Washington pass predominantly through residential backyards, places where landscape decisions are often made without attention to community norms (Nassauer, 1993). Common metrics of watershed land use, flow regime, and biological condition (including ours) do not account for the effects of local landowners' decisions about streams on their property. This phase of the study was a prototype effort to fill a gap currently present in virtually all stream assessments in the Pacific Northwest and elsewhere. It emphasized individual behavior, not attitudes or opinions, because people often do not do as they think or say (Anderson, 1996).

The assessment of human behavior combined mailed questionnaires, interviews, and on-site visits (Schauman, 2000). The questionnaires were mailed to 520 streamside homes in three basins with a range of property values and urban density, but all adjacent to streams with active salmon runs and are extremely valuable habitat. Ninety-six (18%) completed surveys were returned. No follow-up measures were taken to increase the response level. Data were compiled using an analysis of means. Forty sites were photo surveyed to depict actual practices for comparison with preferences stated in the mailed questionnaires. The private properties ranged from those in watersheds having county-funded outreach programs, including a stream steward, to backyards in neighborhoods with little community awareness of their local streams.

RESULTS

Changing Land Use Influences Biological Condition

Biological condition as measured by B-IBI generally declined as urban development measured by TIA increased (Figure 4). TIA alone, however, cannot be used to predict biological condition at a given site. The upper limit of attained biological condition correlates well with the overall measure of urban development, displaying a "factor ceiling distribution" (Thomson et al., 1996) that defines the best biological condition associated with a given degree of watershed imperviousness (dashed line at upper edge of data in Figure 4). Yet degraded streams (low B-IBI) may occur at any level of watershed imperviousness; highly variable biological conditions were particularly evident at low to moderate development levels (see also Karr and Chu, 2000). As development intensity increased, the range of biological condition narrowed; in the most urban watersheds, conditions were uniformly poor. Across all study sites, B-IBI correlated significantly with urban land cover (i.e., the combination of "intense," "grassy," and "forested" urban categories) at the three spatial scales: ***subbasin*** (r = - 0.73, $p < 0.001$, n = 34); ***riparian*** (r = - 0.75, $p < 0.001$, n = 34); and ***local*** (r = - 0.71, $p < 0.001$, n = 31) (Morley and, Karr 2002). Riparian and subbasin land cover was highly correlated (r = + 0.98, $p < 0.001$, n = 34), but local and subbasin land cover was not.

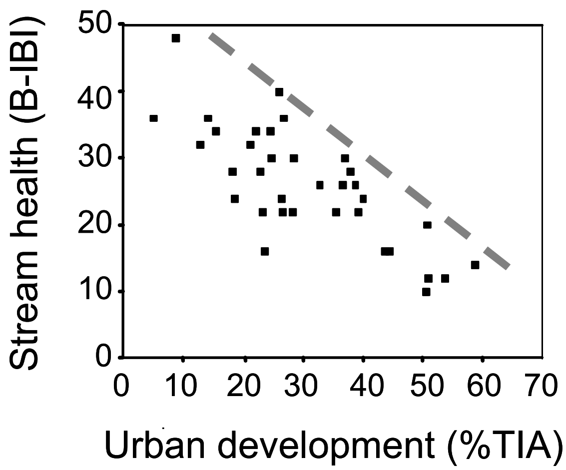

Figure 4: Stream health (measured using the benthic index of biological integrity, B-IBI) declines as subbasin urbanization (measured by total impervious area, TIA) increases. Plotted samples collected in 1997, 1998, and 1999.

Associations between urban development and stream condition have been explored for more than two decades. "Impervious area," commonly defined as the fraction of the contributing watershed that is paved or covered with buildings, is the most common metric used to capture development intensity. The earliest systematic study of the relationship (Klein, 1979) reported a rapid decline in biological diversity where watershed imperviousness exceeded 10 %. This observation gave rise to the expectation that keeping development below 10−15% TIA (a "threshold-of-effect") would protect stream health (see Klein, 1979; Booth and Reinelt, 1993; Schueler, 1994; Schueler and Holland, 2000; Paul and Meyer, 2001; Beach, 2002).

Other studies, however, point out that stream condition reflects a far more complex interplay of factors than a simple threshold of impervious surface can take into account (Steedman, 1988; Karr and Chu, 2000; Segura Sossa et al., 2003; Alberti et al., in press). For example, a wide range of stream conditions may be associated with low to moderate imperviousness, reflecting watershed sensitivity (as due to soils and surficial geology; Allan et al., 1997; Booth et al., 2003); the spatial patterning of impervious area and other modified land cover on the landscape (Steedman, 1988; Fore et al., 1996; Segura Sossa et al., 2003; Alberti et al., in press); and the effect of point sources of pollution and other human activities (Karr and Chu, 2000). Indeed, detailed work in the Pacific Northwest and elsewhere has often demonstrated substantial biological degradation at TIAs below 10% (May et al., 1997; Booth and Jackson, 1997; Karr, 1998; Horner and May, 1999; Karr and Chu, 2000; Booth et al., 2001), a fact that is now recognized by some prior proponents of the 10−15 % "threshold" (e.g., Center for Watershed Protection, 2003). Thus, although data from this and previous studies may support the use of TIA as a broad index of certain forms of human disturbance and perhaps as an upper bound on potential stream condition, they do not justify its use as a predictor of stream health or as a guide to "acceptable" thresholds of development.

Hydrologic Change Imposes Basinwide Stress

In selecting T_{Qmean} and $T_{0.5\ yr}$ to explore the hydrologic effects of urban development, this study abandoned traditional emphasis on the damage caused by massive flooding on urban infrastructure such as roads, industrial parks, and homes. Two new metrics succeeded in capturing the hydrologic effects of urbanization, despite local variability in soils, geology, and watershed topography among Puget Sound lowland basins (Table 1). For example, T_{Qmean} varied from 0.26 in Mercer Creek to 0.42 in Jenkins Creek; as TIA increased, both T_{Qmean} (r = -0.61, p = 0.008, n = 15) and $T_{0.5\ yr}$ (r = -0.72, p = 0.003, n = 13) decreased significantly (Figure 5). Other influential factors (e.g., size, geology, topography of watershed) are likely responsible for some of the unexplained variation.

Stream biological condition also varied significantly with these streamflow metrics (Figure 6a, b); B-IBI is higher in less flashy watersheds (more stable flow regimes). Correlation coefficients were comparable for relationships between both streamflow metrics and biological condition, as well as between land cover and biological condition (r = -0.84, 0.82, and 0.80 for B-IBI vs. %TIA, T_{Qmean}, and $T_{0.5\ yr}$, respectively; $p < 0.001$ in all cases).

A major advantage of the flow attributes, however, is that they provide a more mechanistic basis—a more precise diagnosis—for understanding the causes of biological degradation (e.g., flashy discharges) beyond what is revealed from a simple correlation with TIA. For example, among nine streams with local urban land cover data available, all sites with local urban land cover of 54% or more fall below and to the right of the main trend (Figure 6c);

that is, the sites' biological condition was poorer than hydrologic conditions alone would have predicted. In contrast, sites with less local urban land cover (here, 14–53%) fall above and to the left of the main trend, meaning that biological condition was better than predicted by hydrology. No similar secondary patterns are discernible on a plot of TIA vs. B-IBI (e.g., Figure 4).

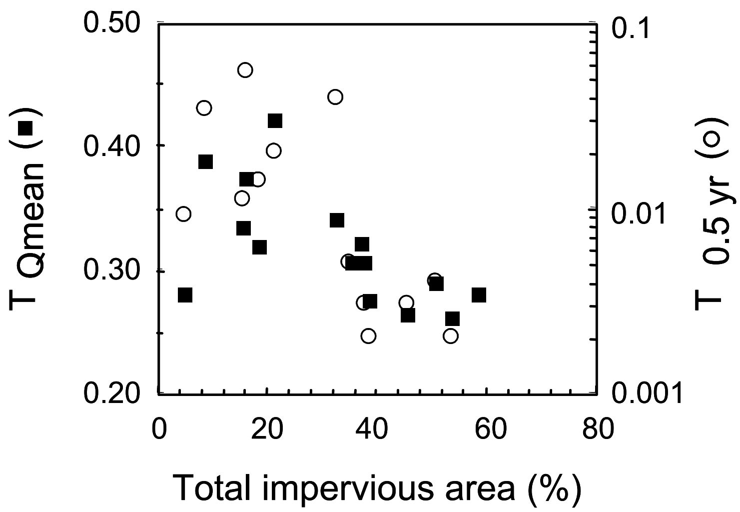

Figure 5. Discharge flashiness as measured by two hydrologic metrics (T_{Qmean}, left axis; $T_{0.5\ yr}$, right axis) (lower = flashier).

Available data do not allow us to identify a sole cause for these patterns. In some cases, variability is probably due to the influence of local land cover, but in others watershed hydrology may play the bigger role. For example, the Jenkins Creek site (JE971) had a "fair" B-IBI of 32 and an intermediate TIA (21%). This apparent correspondence masks one of the least flashy watersheds in the region (T_{Qmean} = 0.42, highest in the study), where very high infiltration greatly reduces surface runoff despite a history of channel straightening and minimal riparian forest near the sampling site. These conditions are readily interpreted from the T_{Qmean} vs. B-IBI relationship (see Figure 6) but are not at all evident from the plot of TIA vs. B-IBI (see Figure 4).

Even with ecologically appropriate measures of flow, however, one must remember that stream conditions are not determined solely by flow regime, which in turn is not determined solely by urban development. Intrinsic watershed characteristics—watershed geology, soil permeability and depth, topography, channel network, and climate—are also relevant (Booth et al., 2003). Thus no single watershed indicator should be expected to predict flow regime or all the consequences of changes in flow for stream conditions.

Actions by Individuals Impose Local Stress

The assessments of human behavior, specifically the actions of individual landowners, indicated substantial variation in backyard stream condition, reflecting an equally wide range of choices made by individuals in their private space. The private properties studied ranged from those adjacent to streams and located in watersheds having county-funded outreach programs, including a stream steward, to backyards in neighborhoods with little community awareness of their local streams. In all locations the range of conditions varied from benign neglect to severe, "ecopathic" alteration of private streamside property. Although no obvious simple explanation for these differences in behavior emerged, the behaviors nonetheless resulted in locally significant influences, whether benign or damaging, on stream health.

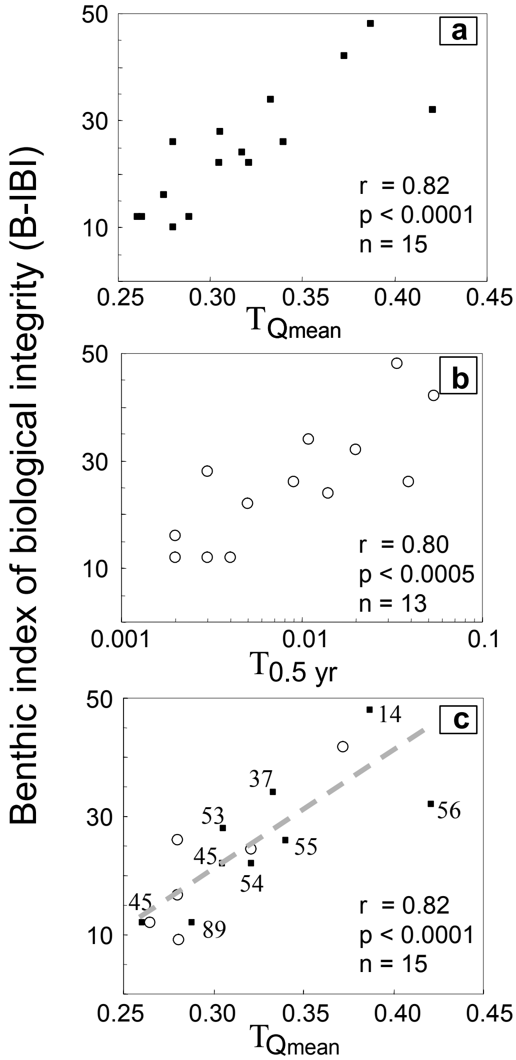

Figure 6. Relationship between benthic index of biological integrity and (a) T_{Qmean} and (b) $T_{0.5\ yr}$. In (c), numbers indicate local urban land-cover percentage; sites plotted as circles lack local land-cover data.

Respondents were asked "What would most likely be your choice for three typical landscape design goals: Privacy and boundary design, individualistic design, or ecological care?" Of these three goals, "ecological care" was mentioned most often in the surveys, although the differences among the mean values for the different goals were not statistically significant. When asked on the mailed survey to specify the three "most important considerations in their landscaping or gardening," however, fewer than 10% of respondents indicated that any ecological considerations were important. The overwhelming response (>75%) to this question was "low maintenance." Many respondents repeated this desire three times: ease of maintenance dominated all other concerns.

Analysis of photos taken during site visits to the homes where "ecological care" rated as the highest goal showed some ecologically caring behaviors, such as composting, but no actions that could be described as streamside rehabilitation or restoration. The most prominent "ecological care" behavior was to comply with stream corridor buffer regulations in newer subdivisions on lots with a steep grade separating the backyard from the stream. No one planted buffers in older subdivisions, however, where trees had previously been cleared.

In 4 of the 40 photo-surveyed backyards, elaborate landscape designs included one or more artificial ponds reaching the high groundwater table adjacent to the stream (Figure 7). In another case the lawn stream edge was mowed for more than 60 m with two concrete vaults set into the bank, which the resident described as “salmon rearing boxes.” Residents were proud that each year they raised silver salmon (*Oncorhynchus kisutch*) fry obtained at local hatcheries for release into the stream. They always had backyard gatherings and parties to watch sockeye salmon (*O. nerka*) spawn. Such residents place high value on their direct experience with fish.

Figure 7. Backyard stream. Rock banks, grass to stream edge, straightened channel, symmetrical plantings installed by streamside neighbors in the name of “stream enhancement.”

In suburban sites older than 10 years, many backyards contained benches on lawns along the stream edge. In newer subdivisions where a riparian buffer was mostly intact, streamside benches had been placed at the end of a path leading through the buffer from the family’s part of the backyard. These were often simple settings where one person might sit to contemplate nature. Clearly, people desire direct connection with their streams, but this desire did not always translate into positive acts. Given continuing, massive outreach and education efforts throughout the region, a few instances were anticipated where individuals would have planted buffers or attempted to revegetate the banks, yet none were found. Instead, banks were cleared along all streams.

Thus, individuals often do not take personal responsibility for rehabilitation on private property, even though many of the same residents may recognize “salmon habitat rehabilitation” as a worthwhile regional goal and take personal pleasure in its success. The factors responsible for this behavior are no doubt numerous and tangled, a mix of wanting maintenance ease along with enhancement of salmon populations and river health. The lack of clear guidelines on what to do and how to do it probably also plays a big role, however, as is clear at an institutional level from the efforts to release hatchery fish despite overwhelming evidence that doing so is unlikely to produce more salmon or healthier rivers (Lichatowich, 1999).

The importance of local stressors can also be demonstrated within a watershed context. Measured biological condition changed substantially along a section of Little Bear Creek (Figure 8), despite nearly identical subbasin TIAs for all sampling sites. Variations in riparian land cover in the 1-km upstream zone (“local”) and even greater differences in conditions immediately adjacent to each sampling site, however, are strongly correlated to the variation in biological condition. The changes are evident in the area of Figure 8 and even more so in the watershed as a whole; for example, B-IBI was 40 at a site 5 km upstream of the pictured area, where more extensive riparian forest and wetlands remain. In the image, dark areas are forest or low-density residential areas; light areas are primarily industrial sites along a state highway that parallels the creek and exits the view in the upper right corner.

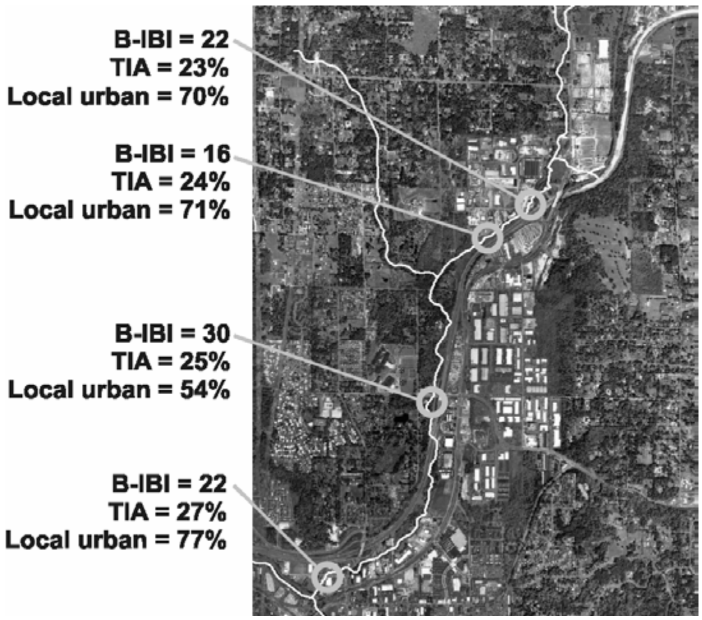

Figure 8. Variation in biological condition (B-IBI) along a section of Little Bear Creek near Woodinville, Washington, despite nearly identical subbasin TIAs at all sites. Pictured area covers 3.4 by 4.6 km.

SYNTHESIS AND MANAGEMENT RECOMMENDATIONS

This research demonstrates that impervious area is not a reliable surrogate of biological condition, despite a pattern of broad biological decline with increased impervious area. Impervious area does provide a rough measure of the watershed area people have appropriated, and therefore it serves as a proxy of human influence. But as such, it cannot define the specific nature of human influences in a watershed or serve as a surrogate for biological condition. Direct biological measures are essential to infer stream health and to help diagnose the likely causes of degradation.

Important lessons for urban stream management emerge from the relationship between land use and biological condition. First, urbanization does not affect all streams the same way. The degree of urbanization and the specific complex of activities characterizing local development differ for each stream. The result is a lack of a precise association between stream health and urban development (Figure 9, left). Variation in biological condition is high at low levels of development but less variable as development increases (wedge shape). Second, any effort to manage a specific stream must relate stream biological condition to specific human activities and their effects in that watershed. Not doing so is akin to prescribing a cure for an ill person without identifying his symptoms or looking for their likely causes.

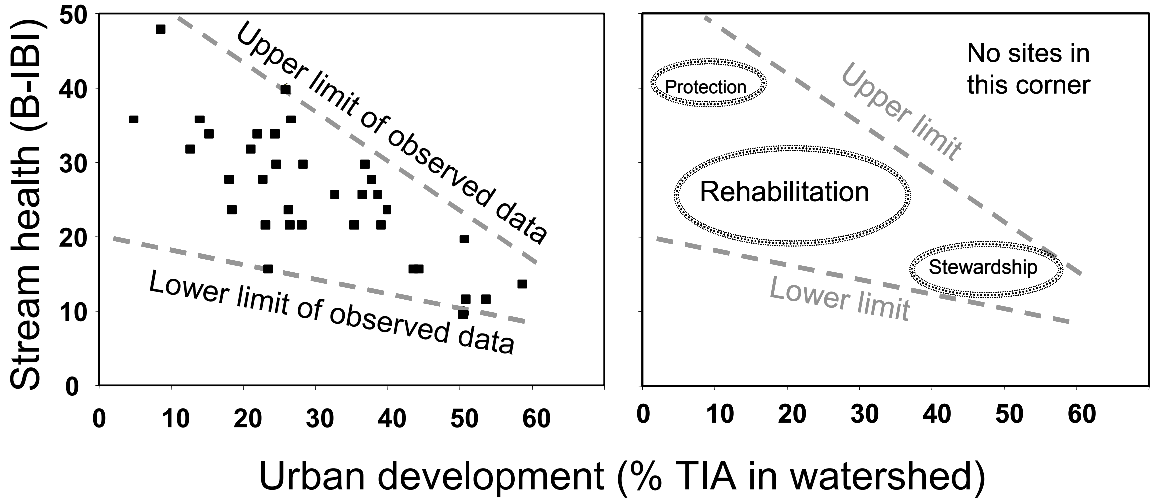

Figure 9: Left: Association between stream health (benthic index of biological integrity; B-IBI) and urban development (% total impervious area; TIA). Right: Recommended primary management strategies.

Although individual urban streams demand individual rehabilitation plans, some general guidelines apply (Figure 9, right). Streams or stream reaches in the upper left of the figure (labeled "Protection") support the richest biota and the highest biological condition, perhaps approaching biological integrity or the state of the least-disturbed comparable streams in the region. Such areas should be targeted for priority protection and long-term conservation. The best streams to protect can be chosen using any number of methods, including B-IBI, as long as the method relies explicitly on biology. In King County, Washington, for example, the 1993 "Waterways 2000" initiative identified high-quality stream reaches and watersheds so that available funding could go toward purchasing development rights or toward outright acquisition. First, a committee of scientists and citizens used existing information to select watersheds in the best biological condition at the time. They considered the number of salmon species; number of vertebrate species in the riparian forest; presence of other native fish, amphibians, or aquatic invertebrates in each watershed; plus the percentage of developed area, forest cover, or protected lands and the percentage of stream length with 90-m-wide adjacent forest. Within watersheds ranked highest under these criteria, they then evaluated areas for potential acquisition by a second set of reach-scale criteria, including riparian forest size; riparian forest structure (stand age, species distribution); connectivity to other habitats and features; local richness and abundance of aquatic species; and such geomorphic conditions as braided areas, confluences, flood channels, and sources of gravel and groundwater. Countywide, using the first set of criteria, six watersheds were identified having a combined area of more than 1200 km^2, and, using the second set, the county eventually acquired or otherwise permanently protected more than 8 km^2. One such protected place lies along Rock Creek (Figure 10), whose B-IBI was the highest (48) of all measured sites in the Puget Sound region even though it has a low but not the lowest subbasin total impervious area (TIA = 9%). However, it also has highly infiltrative watershed soils yielding a T_{Qmean} of 0.39 (second-highest among the sites) and an already well-protected riparian corridor (local urban land cover = 14%, least-disturbed of the sites).

Figure 10. Rock Creek, with the highest benthic index of biological integrity (B-IBI = 48; maximum = 50) in the Puget Sound region.

Another portion of Figure 9b (labeled “Rehabilitation”) includes sites whose biological condition is moderately to severely degraded despite only little to moderate watershed urbanization. Improving such streams may be possible, but only after identifying the specific factors responsible for degradation and treating their effects. Individual behavior is especially important in these lightly and moderately developed watersheds, because individuals’ choices affect both localized stream reaches and the larger watershed, where political control over land use and stormwater regulation ultimately determines flows, pollutant loads, and channel and riparian condition. Where these effects are limited or easily treated, a stream might be restored close to minimally disturbed conditions. But in other cases, the best hope may consist only of small improvements. Careful evaluation is the only way to direct public resources toward streams where real improvements can be achieved, lest limited funds be spent on rehabilitation projects with worthy goals but no biological outcome (e.g., Larson et al., 2001).

The third major section in Figure 9b (labeled “Stewardship”) encompasses places where urban development is virtually complete, and biological condition is at its worst. Such places are often subject to a number of the most harmful human effects, including hydrological and stream channel modifications and substantial pollutant and sediment loads. The results (and common sense) show that, regardless of locale, neither widespread riparian replanting nor extensive hydrologic rehabilitation is feasible, and efforts to do so are unlikely to much improve biological condition. For example, Figure 11 displays two contrasting streams where riparian conditions are vastly different but their influence is overwhelmed by watershed urbanization. The left panel of Figure 11 shows Thornton Creek in NE Seattle (subbasin TIA = 51%; local urban land cover = 89%; T_{Qmean} = 0.29; B-IBI = 12, “very poor”); the right panel is Miller Creek (subbasin TIA =

54%; local urban land cover = 45%; T_{Qmean} = 0.26; B-IBI = 12), which drains the western half of Seattle-Tacoma International Airport. Thus, measuring riparian condition alone is not adequate to gage stream health, and replanting riparian zones does not guarantee improved stream biota.

Figure 11. Contrasting riparian conditions in two highly urbanized watersheds. Left: Thornton Creek (B-IBI = 12, "very poor"). Right: Miller Creek (B-IBI = 12, also "very poor").

In such settings, the opportunity to protect such places has already been lost and full restoration is almost surely impossible. That said, however, people can "do no [further] harm" to such streams and can even improve conditions for both stream life and the people that live nearby. Neighborhood efforts—cleaning up, removing nonnative vegetation, replanting, even just leaving reaches alone—can improve local biological health, provide community amenities, and raise public support for regional enhancement efforts that may offer better hope for watershed-wide recovery (Groffman et al., 2003). Improvements in heavily degraded areas can also reduce downstream effects and help protect or rehabilitate downstream reaches.

In general, most urban streams flow through watersheds under significant human influence but where modest improvement is fully appropriate and achievable. Management programs, however, should rely neither on piecemeal application of structural best management practices (Booth and Jackson, 1997), nor on spot efforts to replace lost wildlife, for example by releasing hatchery fish that need whole healthy watersheds to survive. Such activities simply treat symptoms without dealing with the larger syndrome of diverse human influences.

Even for "modest" rehabilitation goals, therefore, as many of the following seven actions as possible are defensible and recommended:

1. Cluster development to protect most of the natural vegetative cover, especially in headwater areas and around streams and wetlands, so that riparian buffers remain intact (Booth et al., 2002; Morley and Karr, 2002).
2. Limit watershed imperviousness, either through minimal development or by reducing the "effective" impervious area through the widespread reinfiltration of stormwater (Konrad and Burges, 2001).
3. Mimic natural flow frequencies and durations, not just control peak discharges, when designing stormwater detention ponds (Konrad and Burges, 2001).

4. Protect riparian buffers and wetland zones, and minimize road and utility crossings (Morley and Karr, 2002; Meador and Goldstein, 2003; Alberti et al., in press).
5. Begin landowner stewardship programs that recognize the unique role of adjacent private property owners in rehabilitating, maintaining, or degrading stream health.
6. Apply knowledge from multiple disciplines—toxicology, hydrology, geology, biology, ecology, environmental design, public policy—and communicate that knowledge to all groups involved.
7. Stress the importance of measuring stream biota directly—along with physical, chemical, and landscape features—to diagnose causes of degradation, track the effectiveness of management programs, and connect regulations and incentives directly to both public preferences and legal mandates (Karr and Chu, 1999; Morley and Karr, 2002).

A major lesson of this analysis, then, is that fully restoring all developed and undeveloped watersheds is not feasible. This work has found no evidence that the impacts of urban development can be fully alleviated; in other words, there are no examples, in this or any other study, of sites that would fall into the upper right corner of Figure 9. People routinely underestimate the levels of mitigation needed to truly restore streams (Barker et al., 1991; Booth and Jackson, 1997; Jackson et al., 2001). Even if restoration were technically possible, people are unlikely to commit enough money or to commit to wholesale changes in land use in highly urbanized areas. Thus the key tasks facing watershed managers, and the public who can support or impede their efforts, are to identify watersheds where existing low urbanization and associated high-quality stream conditions warrant development strategies that protect the existing quality of these systems and to improve management of those watersheds where some rehabilitation is possible. In places where rehabilitation is likely to be successful, improving flow regimes and near-stream conditions are top priorities because of their demonstrated biological consequences.

Managing urban streams requires a blend of science, public policy, and individual actions (Karr, 2001). Society can no longer afford piecemeal fixes of only one driver of degradation (such as water quality, stormwater runoff, or land use planning); neither can society afford seemingly broad yet actually narrow goals (such as restoring salmon). Only by integrating what is known about stream locale, including landowner behavior; diagnoses of degradation's causes; and evaluations of biological condition can urban conservation or rehabilitation goals be accomplished. Success also will require agencies, institutions, and diverse stakeholder groups to coordinate their efforts (Wang 2001) and to go beyond a poorly articulated "balance" between ecological protection and social and economic costs (e.g., Pickett et al., 1997).

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